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Compliance monitoring using synchrophasor technology in Indian power system

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SUMMARY

Standards and regulations are implemented in power system to ensure reliable and secure operation of power system. Thus, it is important to monitor the compliance of these regulations and standards to ensure that each equipment is working as per defined capability and is following all the regulations/standards/codes during varying operating condition. Any compliance monitoring requires adequate data through which such compliance can be ensured. With conventional SCADA data, steady state performance can be complied however power system being dynamic many such compliance could not be ensured directly. However, with synchrophasor data many compliances related to dynamic nature can be effectively ensured. This paper provides some of the use cases of synchrophasor data for compliance monitoring in Indian power system.

KEYWORDS

Distributed control system (DCS), Frequency response characteristics (FRC), Indian Grid, Inertia, Phasor measurement units (PMUs), Supervisory control and data acquisition system (SCADA),

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1. Introduction

Monitoring compliance of various standards and regulations in the power system by all users of the grid is one of major activities for making grid operation secure. It helps in ensuring the performance of various equipment as per the set technical standards as well as regulatory provisions. In most of countries, responsibility of the compliance monitoring and validation lies on the independent system operator (ISO). In general, such compliance are checked with

- Availability of correct SCADA data at control centre which updates at 4-20 second's rate
- Voltage and current recorded by field recorder like disturbance recorder (DR)/ transient fault recorder (TFR) which are equipment specific and have 5-10 seconds data storage capability.
- Generating plant distributed control system (DCS) data which update at 0.5 -1 second interval

This usually makes compliance monitoring and validating models of various devices during dynamic power system phenomena a challenging task. However, many such responses are dynamic in nature and are interlinked which cannot be assessed directly unless data of high resolution is available with the monitoring agency. For such issues, PMUs based synchrophasor data has become a major tool through which many such compliance monitoring activities are being achieved. This paper provides a brief overview of several compliance monitoring functions which have been achieved using synchrophasor data with several case studies.

2. Wide area measurement system (WAMS) in Indian power system

Indian Power system adopted synchrophasor technology since the year 2010. It started with 4 PMUs and gradually now there are more than 1700 PMUs connected to the system for power system dynamic monitoring. Several online and offline applications based on synchrophasor data are being utilized in the Indian power system. Among offline applications, compliance monitoring is one of the most sought utilizations of synchrophasor data.

3. Compliance monitoring using synchrophasor

In the Indian power system, following are the major compliance monitoring utilization of (WAMS) technology:

A. Frequency response compliance
B. Inertia and frequency response model
C. Voltage stability compliance
D. Voltage unbalance
E. Generator model validation
F. Controller tuning and performance validation
G. Fault ride through performance of wind power plants
H. Protection system performance
I. FACTS devices (SVC/STATCOM) dynamic performance

A. Frequency response compliance

With increase in penetration of PMUs in the power system, generating units or the power plant are being monitored through PMUs which provide high-resolution data directly from their high voltage or low voltage generating transformer terminal. This enables monitoring of dynamic behaviour of individual generating units. Another way is to monitor entire power plant's dynamic behaviour. This can be done with placement of PMUs on its evacuation lines. Both options help in monitoring of entire plant dynamic behaviour with high sampled data. One of the best applications of such PMU data would be the checking of frequency response compliance.

Frequency response is also known as primary frequency response (PFR) or governor response. Primary frequency response (PFR) monitoring enables verifying performance of individual generating units/generating facilities following Frequency measurable events (FMEs) in accordance with requirements of standards or grid code or interconnection guidelines as applicable. PFR is automatic, not driven by any centralized system, and begins within seconds after occurrence of event rather than minutes. It responds to changes in load-generation imbalance which is observed as changes in frequency changes. Because the loss of a large generator is much more likely than a sudden loss of an equivalent amount of load, frequency response is typically discussed in the context of a loss of a large generator [1].

With conventional SCADA data many times monitoring of primary frequency response becomes a challenging task. SCADA data which is not time-synchronized and has lower samples per second resolution does not reflect the true primary response. Thus, compliance monitoring becomes a challenging task. With synchrophasor data, this compliance monitoring is now very accurate and entire plant dynamic behaviour during frequency response events can be observed [2].

One example for frequency response compliance monitoring is provided below. In India, generating plants have to provide governor response up to 105% of their running capacity (generation level) during a frequency event. In **Figure 1** PMUs are installed at various power stations' outgoing lines. PMU monitors the net of ex-bus power evacuation through the transmission lines from various power plants. Thus, summation of power flow through all evacuation lines of generating station provides the overall plant power output after its auxiliary power consumption.

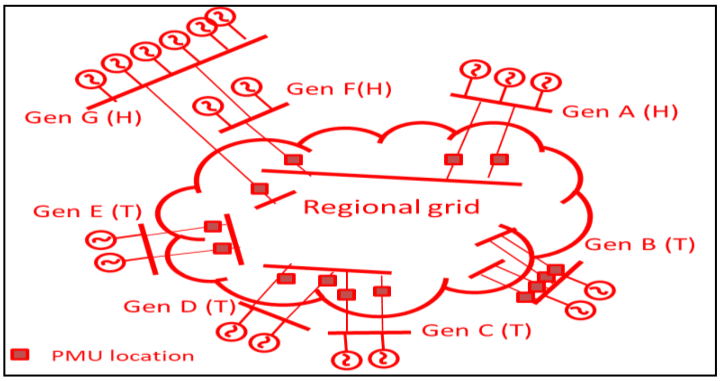

Figure 1 : Schematic of power plant monitoring through PMUs for primary response validation and compliance monitoring.

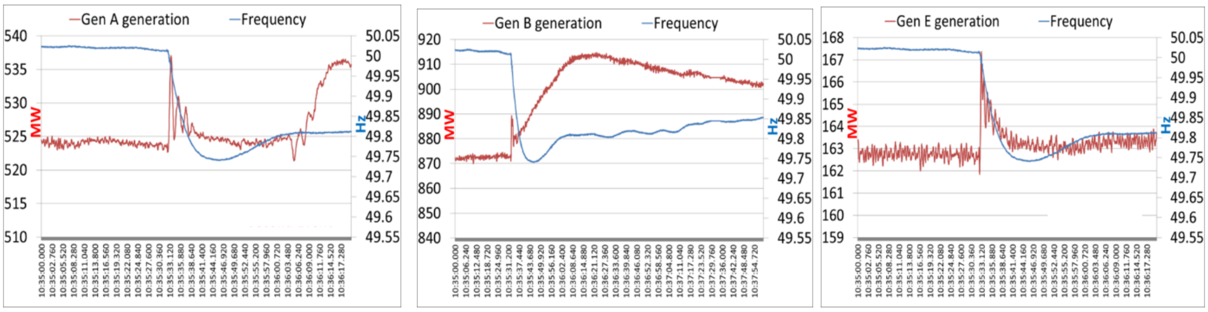

Figure 2: Power plant A, B and E response during frequency event.

Figure 2 shows the response of power plants A, B and E respectively during a frequency event caused by generation loss in the Indian grid. It can be observed that generating plant B has provided a good response. Its generation has increased through governor fast valving action post event, and it provided a sustained good response. While generating plant A has provided a good initial response however, its response got withdrawn quickly and oscillation is observed in overall plant output. Further, after around 1 minute its generation further increased. This provided the input that governor control is not properly tuned. In case of power plant E, its generation increased promptly with frequency drop however the response could not be sustained and withdrawn immediately in next 30 seconds. This helped the compliance monitoring agency to provide feedback to power plants A and E to tune governors to improve their primary frequency response.

B. Inertia and frequency response model

Inertia monitoring and assessment are one of the important requirements in today's power system with introduction of inverter-based generation and load at large scales. The lower inertia of power system can pose several challenges to grid operators. The methods to estimate inertia in power system is provided in **Figure 3** [3,4]. Earlier inertia assessment was majorly related to offline study. However, with advent of PMUs, inertia estimation during disturbance has provided a good validation of the system inertial response. Another important aspect is rate of change of frequency (RoCoF) which can also be evaluated using PMUs post any frequency event. However, as RoCoF varies with electrical distance from event so from power system perspective RoCoF of centre of inertia is generally considered. Exact estimation of centre of inertia is a difficult task however with availability of adequate number of PMUs observability has improved and this can also be determined effectively.

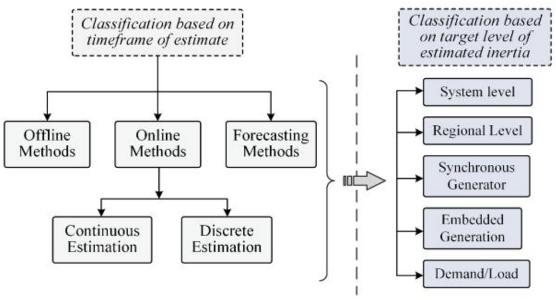

Figure 3: Classification of inertia estimation methods [3]

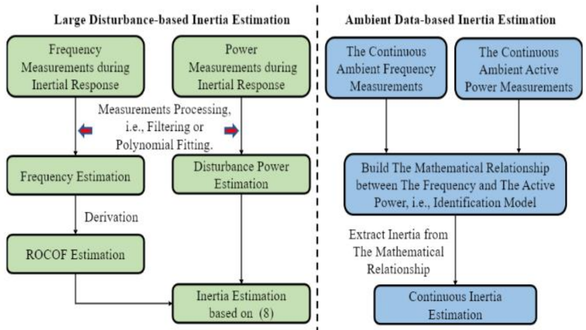

Figure 4: general process for measurement-based inertia estimation [4]

Based on PMUs, there are two methods, one of which is large disturbance based and the other is ambient data-based inertia estimation. The general process of these two methods is provided in **Figure 4**.

In India, PMUs have been utilized for inertia assessment as well as for RoCoF assessment [3]. With more than 1400 PMUs providing wide observability of the entire system, the RoCoF estimation for system inertia calculation has been performed for various events. First, it uses the raw data from multiple PMUs from various nodes in the power system followed by removing noise and oscillations through filters. This is then followed by average frequency calculation to get the frequency for centre of inertia. The average frequency is then utilized for RoCoF calculation using rolling over window and calculated RoCoF is used in swing equation for inertia estimation. The estimated inertia was validated with model-based analysis and found to match with it closely. The estimated inertia in Indian power system over last 8 years is provided in **Figure 5**.

Further, it has also given input on RoCoF and Inertia requirements with increasing renewable energy penetration. **Figure 6** shows one of the analyses of estimated inertia and its gradual reduction with increasing RE penetration.

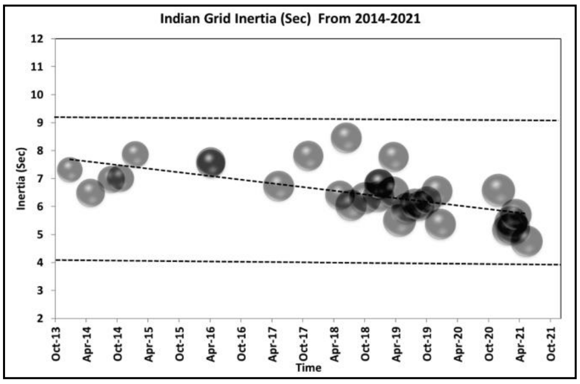

Figure 5 : Inertia calculated from synchrophasor data in Indian power system.

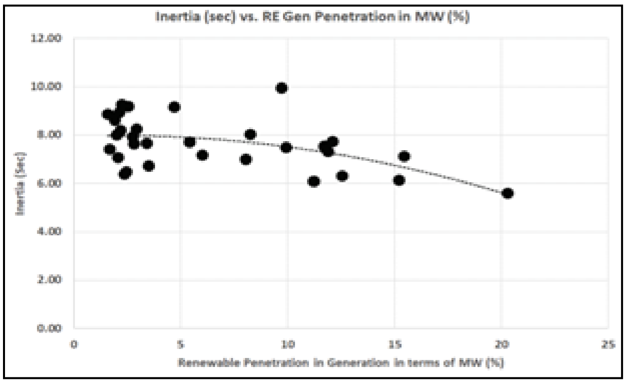

Figure 6 : Inertia vs RE penetration

C. Voltage stability compliance

Power system dynamics influencing voltage stability are usually slow, therefore steady-state (power flow) analysis generally offers an effective way to perform voltage stability assessment (VSA). Power – voltage (PV) and voltage–reactive power (VQ) curves are the most frequently used steady-state techniques for voltage stability assessment in any power system [5]. These provide the available voltage stability margin for a node or any specific area. Usually, online VSA was performed in the operator's state estimator (SE) at its operational rate, which usually occurs every three to ten minutes. This made the entire process slow due to which dynamic voltage stability assessment has become a need for operators. This will provide the steady state as well as dynamic voltage stability margin to the operator.

The advantage of synchrophasor data is that it allows for continuous monitoring of the power system frequency, df/dt and observation of actual voltage conditions. This helps in real-time computation of operating margins at much higher resolution rates as compared to VSA using SCADA and SE data. Synchrophasor data also provides advanced real-time visualization of current operating conditions and voltage stability limits to better assess the power system's proximity to system collapse.

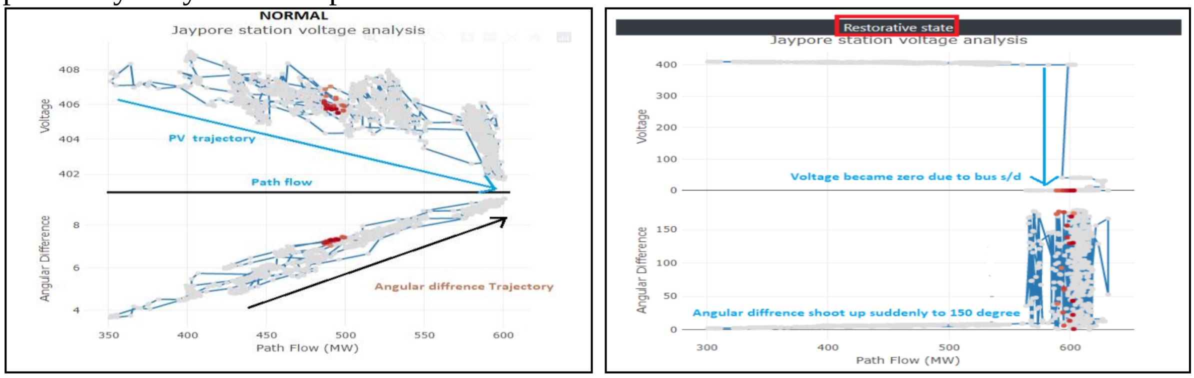

Figure 7 : PV and δP plots for voltage stability assessment

Based on this, PV and P-delta monitoring tool has been developed by POSOCO to monitor voltage stability margin and compliance. This tool on voltage stability has been designed using active power, voltage and angular separation [6]. In any area, angle separation from source to sink is related directly to active power flow. Thus, voltage stability can also be analysed using power angle and voltage of the area. These are corroborated with calculated margin from offline simulation and provide alertness to operators. The display for system operator during normal and restoration operating state are shown using PV and δP plots in **Figure 7**.

D. Voltage unbalance

Phase voltage unbalances in power system is defined through various standard and regulations. There is a set allowable limit up to which such phase unbalance can be tolerated in the power system. In general, there are basically two reasons for phase unbalance in EHV system which are (i) unbalanced loading or types of loads connected and (ii) long transmission line non-transposition. There can also be voltage instrument transformer (VT) or transducer issue which can result in such issues. The magnitude of unbalance of three phases directly impacts protection systems like over voltage and protection of loads.

With availability of PMU data, such voltage magnitude unbalances can easily be monitored in the entire power system. This has helped utilities in finding the root cause of such unbalance and taking adequate remedial measures. The voltage unbalance monitoring can be checked by having a threshold value with which each voltage can be compared [7]. If any phase voltage is exceeding this threshold limit, then this indicates either there is an actual issue or a measurement issue.

One of the examples where VT measuring voltage had an issue and was causing significant unbalance in phase voltage as observed from synchrophasor data is briefly mentioned here [7]. **Figure 8** shows the voltage unbalance observed at one of the substations and based on this field validation was done where CVT issue was observed. After this, CVT was replaced, and it can be observed from the second plot that the unbalance voltage issue got resolved.

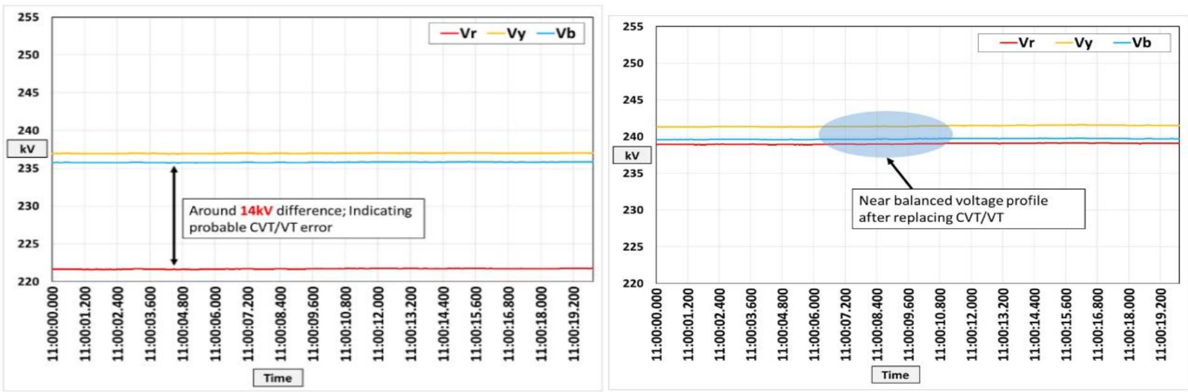

Figure 8: Voltage unbalance due to CVT issue and its rectification [7]

E. Generator model validation

To assess the impact of any equipment on the power system it is essential to have a proper network and dynamic model so that proper studies can be performed. However, models which are being utilised should be validated to ensure that their performance matches with actual behaviour. This helps in assessing the impact of any equipment behaviour on the overall dynamic nature of the power system.

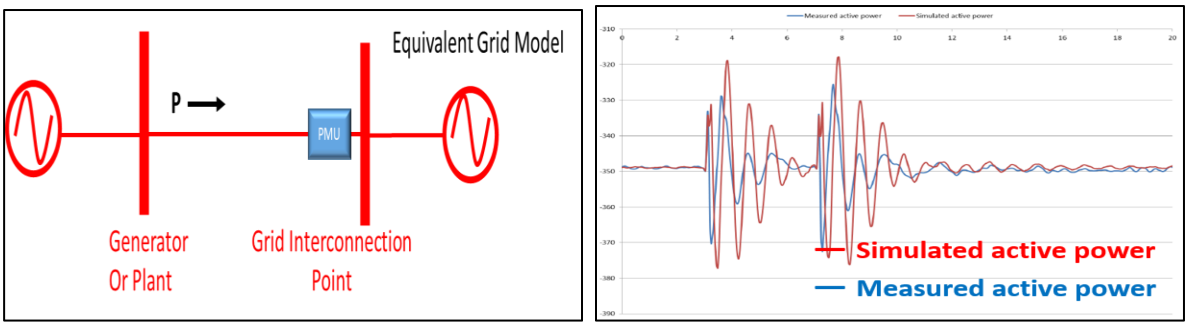

Figure 9 : Model validation using synchrophasor data

With synchrophasor data availability such model validation has become feasible for the system operator without performing several field testing as required for model validation. One such example of model validation for generating unit is shown in **Figure 9**. Here PMU data helped in analysing the model performance.

F. Controller tuning and performance validation

One of the important applications of synchrophasor data availability is for tuning of various controllers present in the power system. This includes tuning of power system stabilizer and power oscillation damping control. Most of oscillatory phenomena in power systems are in the range of 5 Hz and synchrophasor data can measure such oscillation dynamic with a reporting rate of 25 Hz.

Power system stabilizer (PSS) is one of the most effective ways of improving damping in the power system. It is integrated in the excitation control of the generating units and damps observed oscillation by phase shifting the excitation voltage. Being a dynamic issue, synchrophasor data with a high sampling rate provides immense insight in analysing the requirement of PSS tuning during any event [8]. During field tuning activity of PSS, it helps in validating the online performance [9]. After tuning activity, the performance of PSS during any further event also can be analysed.

Some examples of usage of synchrophasor for PSS tuning are discussed below. **Figure 10** shows the assessment of PSS performance at a power plant [8]. The first plot shows the PSS performance in damping generator output power oscillations when PSS tuning was not adequate. Based on this assessment of controller model and event analysis outcome, PSS tuning was carried out and improvement in damping was observed in the second plot in terms of peak-to-peak oscillation and damping time.

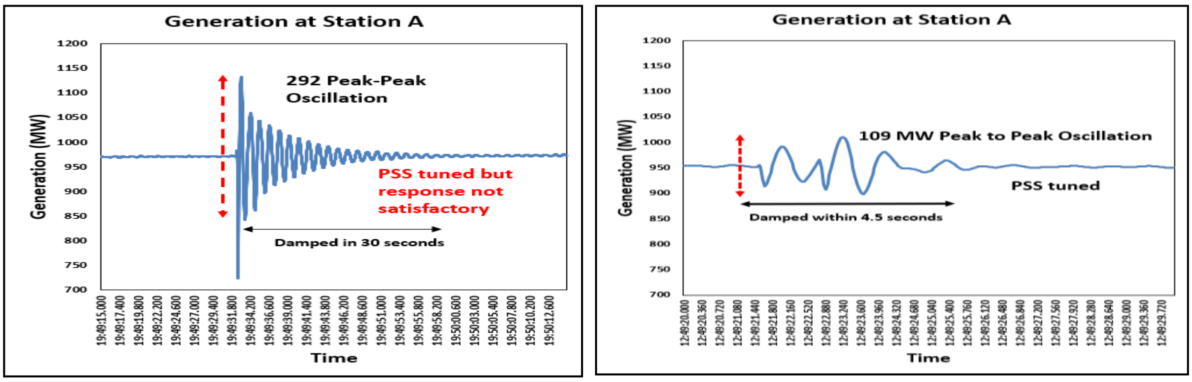

Figure 10 : Improvement of PSS performance on damping of active power at a 1000 MW power plant [8]

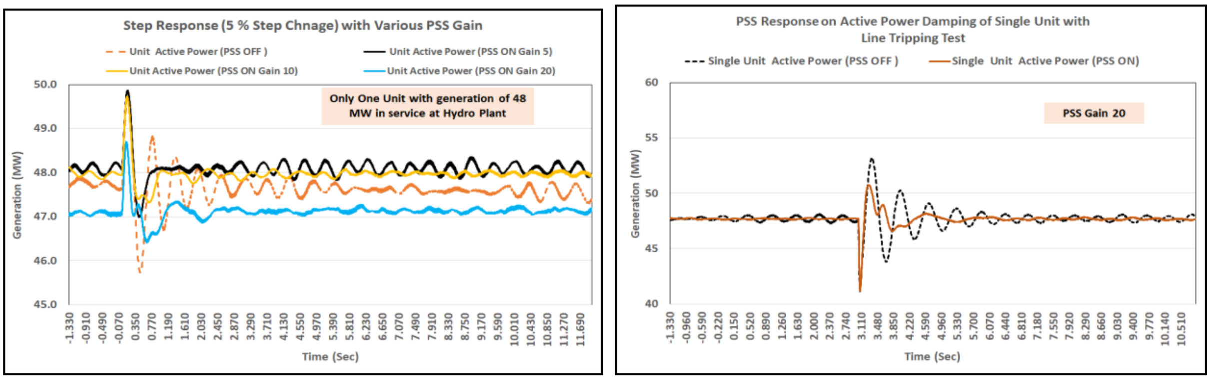

Figure 11 : Step response test and disturbance test at a hydro power plant [9].

Two major tests for PSS tuning are step response and disturbance test [9]. Step response test for PSS tuning provides the response of a single generating unit for any change in voltage reference. It tests the performance of the unit during nominal voltage changes in the power system. The step response test at 5 % step was carried out at one of the hydropower plants keeping one unit in service at a time with varying PSS gain as shown in **Figure 11**.

Disturbance test provides the overall plant response and its more practical as damping it tested with an actual event. It is one of the most effective tests to ensure the actual performance of PSS during an actual event. The disturbance test is done by either switching of transmission lines/ shunt compensation or creating any artificial fault on any of the transmission lines evacuating from the generating plant. **Figure 11** shows the PSS performance of a hydropower plant with line tripping disturbance test when only one unit is in service.

G. Fault ride through for wind and solar power plant

In electric power systems, low-voltage ride through (LVRT), or fault ride through (FRT)/ under-voltage ride through (UVRT), is the capability of electric generators to stay connected in short periods of lower electric network voltage. Such low voltage may appear due to close-in fault near to the generating plant. With increasing penetration of renewable energy, low fault levels it has become one of the major grid connection requirements to be met by inverter-based resources (IBR). In presence of grid voltage dips, a mismatch is produced between the generated active power and the active power delivered to the grid. Modern wind generation systems have the capability of LVRT. PMUs, installed on wind turbine and wind turbine pooling stations are found to be useful for monitoring the LVRT response. One of such incidences has been shown in **Figure 12**, wherein the dip up 0.7 PU due to fault with delayed clearance has resulted in reduced generation by wind power plant [10]. Further, it recovered its active power output with voltage recovery indicating LVRT compliance.

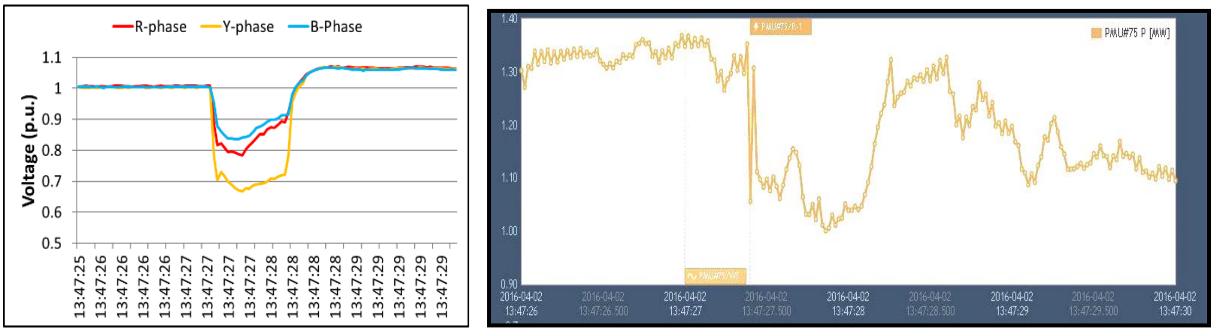

Figure 12: Voltage and Active power plant output of wind power plant indicating LVRT compliance [10]**.**

H. Protection system performance

One of the major applications of synchrophasor has also come out as protection system compliance monitoring. Several use cases are there out of which one important one is coordination of direction earth fault (DEF) protection. One example where DEF operation during high resistive fault were found to be non-coordinated is shown in **Figure 13**. After analysing using synchrophasor data, the same was coordinated.

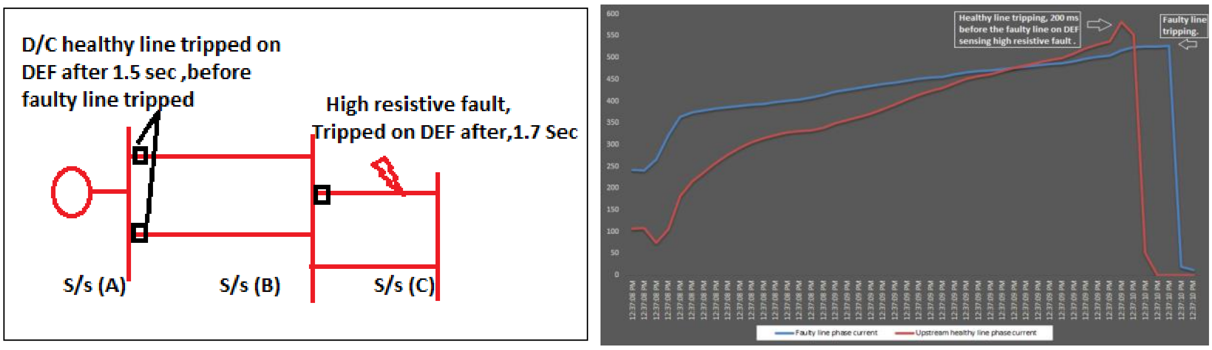

Figure 13: Direction earth fault relay operation for resistive fault and coordination issue

Similarly, the compliance of other protective devices to the operating times specified in CEA Standards for Construction of Plants and Transmission Lines as well as Grid Standards can be verified using synchrophasor data.

I. Dynamic behaviour compliance for FACTS devices

Multiple FACTS devices have been implemented in the Indian power system. These devices improve steady state stability. However, their basic purpose is to improve transient stability. It is obvious that continuous dynamic monitoring and performance assessment is a challenging task. With PMUs installed at the terminal of these devices, now system operator can easily check and validate their performance during any operational scenario as well as during event. One example where steady state, as well as dynamic performance of one STATCOM has been verified using PMU data is shown in **Figure 14**. It can be observed that in one case, MSR was not being switched on due to controller issue and corrected subsequently.

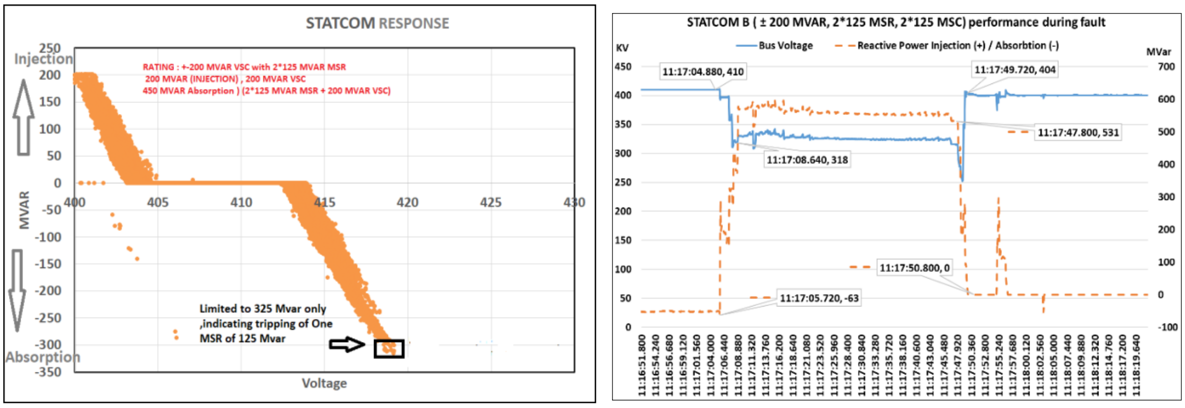

Figure 14 : (a) Steady state and (b) Dynamic performance assessment of STATCOM using synchrophasor data

4. Summary

This paper provides an overview of utilisation of synchrophasor for various compliance monitoring activities in the power system. Most of the compliances which are related to dynamic behaviour of power system can be effectively ensured through synchrophasor data. However, these will require good automation tools for event and signature detection and performance assessment. These monitoring has helped system operator in improving the overall dynamic stability of the Indian power system by implementing correct settings or proper tuning of different devices and controllers.

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